IMPLEMENTATION OF FAA THICKNESS DESIGN PROCEDURE FOR RIGID OVERLAYS

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ABSTRACT

The FEDFAA (for **F**inite **E**lement **D**esign – **FAA**) program was developed from the Federal Aviation Administration (FAA) airport pavement design program LEDFAA, and incorporates three-dimensional finite element (3D-FE) stress computation for thickness design of new rigid pavements and rigid overlays. A practical procedure for incorporating the 3D-FE response into the existing cumulative damage factor (CDF)-based design procedure involves the following:

- The use of modified incompatible modes (MIM) elements for all structural layers in the 3D-FE model, including overlay layers. The MIM element is formulated to give improved bending performance compared to standard eight-node hexahedral elements, allowing a significant reduction in mesh density in bending-dominated layers.

- Implementation of sliding contact surfaces between layers of MIM elements to simulate the interface between overlay and base concrete and between base concrete and subbase layers. Critical stresses are computed at both interfaces in the case of overlays.

- Internal grouping of similar aircraft gears for 3D-FE stress computation. For example, the program was redesigned so that one call to the 3D-FE module now returns all critical stresses for dual-tandem aircraft in the traffic mix. This change allows more efficient computation of critical stresses to conserve run time for mixed aircraft traffic.

This paper presents examples of rigid overlay designs performed using the FEDFAA software, and comparisons with the equivalent designs performed using LEDFAA (based on layered elastic analysis). It is emphasized that the examples presented are preliminary and that due to the change in the response model, it is necessary to recalibrate the rigid pavement failure models that relate computed critical stress to design thickness. This paper also discusses the transition from the VisualBasic™ 6.0 programming environment to the newer VisualBasic.Net™ environment, which offers certain programming advantages.

INTRODUCTION

Practical implementation of the three-dimensional finite element method (3D-FEM) on personal computers (PC) became realistic with an unprecedented increase in the speed and power of PCs in the last decade. Currently, the Federal Aviation Administration (FAA) is developing a new generation of PC-based airport pavement design tools that will employ advanced computer programs based on 3D-FEM technology for new rigid pavements and rigid overlays. These procedures will be capable of designing future airport pavements to serve new aircraft types, including new large aircraft with six or more wheels per gear, which are now in the conceptual stages.

The 3D-FE method can handle greater detail and more complex characterizations of construction materials than layered elastic analysis (LEA). It is particularly useful for modeling rigid pavements, since the slab edges and joints are often the critical components in rigid pavements, and they can be modeled directly with 3D-FEM, something not possible in LEA. In addition, 3D-FEM can incorporate nonlinear and non-elastic material models not available in LEA.

Mechanistic-empirical pavement design programs such as LEDFAA and FEDFAA consist of a traffic model, a failure model, and a structural response model. While the traffic and failure models in FEDFAA remain essentially unchanged from the corresponding models in LEDFAA version 1.3 [1], the structural response model in FEDFAA has been upgraded to incorporate 3D-FEM stress computation for rigid pavements and rigid overlays. The 3D-FEM response module in FEDFAA is an FAA adaptation of the general-purpose FE analysis program NIKE3D [2], originally developed by the Lawrence Livermore National Laboratory of the U.S. Department of Energy. The changes introduced by the FAA added functionality suitable to the rigid pavement analysis problem, and significantly reduced the size of the original program by deleting unused subroutines. LEA continues to be used in the FEDFAA program, both for flexible pavements, and for computing initial thicknesses of rigid pavements and overlays.

Both NIKE3D and the FAA layered elastic program LEAF have been implemented as dynamic-link libraries (DLL) called from a main program designed to run on typical office PCs. The main program is written in the Microsoft Visual Basic language. In a departure from previous FAA programs, the Visual Basic.Net programming environment was used. (Previous programs, including LEDFAA 1.3, were created in the Visual Basic 6.0 environment.)

This paper is primarily concerned with the implementation of the design procedure for rigid overlays, using the 3D-FEM computational approach. Two main developments have made this possible. The first development was the implementation of a 3D-FEM mesh consisting of nonconforming hexahedral elements throughout the entire structure. Through the use of these elements (also called MIM elements), a practical overlay model was achieved. The second development was the optimization and standardization of the 3D-FEM mesh for various aircraft types, which resulted in significantly reduced run times for design traffic mixes. Because of the computationally intensive nature of the 3D-FEM process, further reduction in execution time remains a primary goal of the design procedure development program.

NONCONFORMING ELEMENTS FOR MODELING PAVEMENT LAYERS

Figure 1 shows part of the 3D-FEM mesh used by FEDFAA to model rigid pavement overlays. The basic building blocks of the mesh are the eight-node hexahedral elements, which are assembled as shown to form the various structural layers. Stiffness matrices for the individual elements are formed using the optional MIM formulation available in NIKE3D. A detailed description of the MIM element is beyond the scope of this paper, but a good treatment may be found in Cook *et al*. [3]. In general, MIM elements exhibit superior bending performance compared to standard brick elements and are, thus, suitable for modeling layers such as portland cement concrete (PCC) slabs where the response to aircraft loading is bending-dominated. Because of this superior bending performance, it is possible to justify a density of only one layer of MIM elements per structural layer in the pavement system [4]. In figure 1, for example, the top layer of elements represents the PCC overlay, while the second layer represents the base PCC slab (a different structural component). If normal (conforming) hexahedral elements were used instead, then at least eight layers of elements would be needed to model the same two structural layers to a reasonable degree of accuracy.

A second practical advantage of the MIM elements is specifically related to overlay modeling. Previously, two-dimensional (2D) shell elements were used to model the PCC layer.

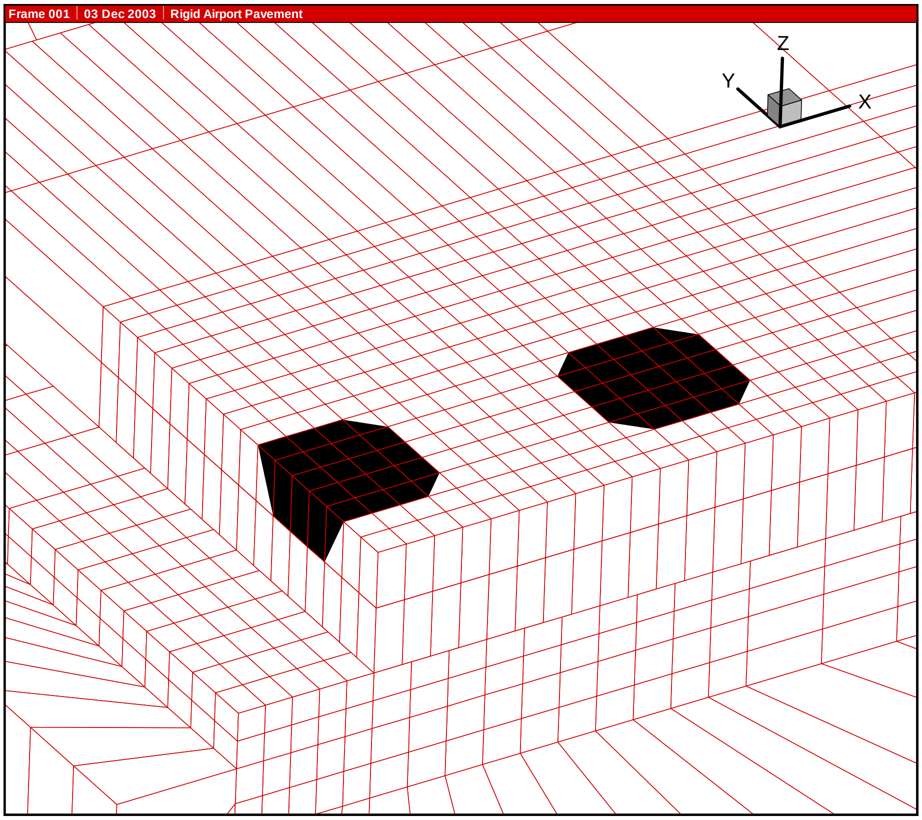

Figure 1. Detail of 3D-FEM mesh for a DC-10-10.

While this approach gave accurate results for bending responses for new rigid pavements involving only one PCC layer, it proved to be impractical for overlay modeling due to restrictions on the number of allowable interfaces involving 2D elements. (NIKE3D allows only one contact surface to be defined on a 2D element, which rules out the use of multiple-shell layers in an overlay model.) This problem was solved by replacing all shell elements with 3D MIM elements. In the current rigid overlay model, NIKE3D contact surfaces are defined on both the top and bottom surfaces of the base PCC layer. Depending on the type of overlay to be modeled (fully unbonded or partially bonded), the properties of the upper contact surface are adjusted. The lower contact surface is always a full sliding surface.

SLIDING SURFACE DEFINITIONS FOR RIGID OVERLAYS

As indicated above, for overlay modeling, more than one sliding surface is defined. The contact surface of the base PCC with the underlying subbase layer is defined as a fully unbonded interface. Depending on the type of overlay, the interface between the base PCC and the overlay is either fully unbonded or partially bonded (i.e., assigned a finite horizontal stiffness to simulate frictional behavior). A partially bonded interface is an intermediate case between a fully unbonded and a fully bonded interface. Unlike a true friction model, the horizontal forces that are transmitted across the partially bonded interface are proportional to the relative horizontal displacement of the two surfaces. A similar partial bond model was previously implemented in the LEDFAA program based on layered elastic analysis. The 3D-FEM model was calibrated to the LEDFAA model. The specific modifications to the NIKE3D source code that were required to implement partially bonded interfaces are discussed in [4].

SELECTION OF FINE MESH ELEMENT SIZE

To make the most efficient use of the 3D-FEM model, the mesh should be the finest in the vicinity of the applied load, which is also the region of greatest interest for computing stresses. The choice of element size in the so-called “fine mesh region” influences both the accuracy of the results and the computational run time. To aid in the selection of an appropriate fine mesh element size, i.e., one that provides good estimates of stresses in rigid pavement layers in a reasonable time, several potential mesh sizes were analyzed for various gear configurations. Fine mesh element divisions of 3, 4, 5, 6, and 8 inches were considered with single wheel, DC-10-10, and B-777 gear configurations. Figure 1 shows the fine mesh region that was generated using the footprint of a DC-10-10 (dual-tandem) main gear. Since both the pavement structure and the DC-10-10 load are symmetric along the *x* axis, only half of the total pavement structure needs to be analyzed by NIKE3D.

Figure 2 plots the variation in horizontal stress computed at the bottom of the overlay slab for the various fine mesh sizes and three different aircraft types: single-wheel load, DC-10-10 (dual-tandem), and B-777 (triple-dual-tandem). Figure 3 plots the run time needed to compute these stresses, also as a function of the fine mesh size. It is clear from a comparison of figures 2 and 3 that there is a trade-off between reasonable run times and accurate solutions. As expected, with an increase in fine mesh element size, there is significant decrease in time of pavement structure life calculation. Based on a series of comparative analyses similar to the one in figures 2 and 3, a mesh size of 6 inches was tentatively selected for the fine mesh area of FEDFAA meshes. This mesh size generally yields values of overlay stress that are comparable with results from finer meshes, with run time requirements that are comparable with coarser meshes.

The reported stresses in figure 2 were computed directly at the Gauss integration points located in the interior of the slab and were extrapolated to the bottom slab surface using a linear extrapolation algorithm. The assumed overlay structure for all runs consisted of a 12-in. PCC overlay (E = 4,000,000 psi); 12-in base PCC (E = 4,000,000 psi); 6-in. stabilized subbase (E = 250,000 psi); 6-in. granular subbase (E = 75,000 psi); and a 15,000 psi subgrade. The run times in figure 3 were obtained using FEDFAA in “Life” mode on a PC with a 2.4 GHz microprocessor, 1 GB RAM, and running the Windows XP operating system.

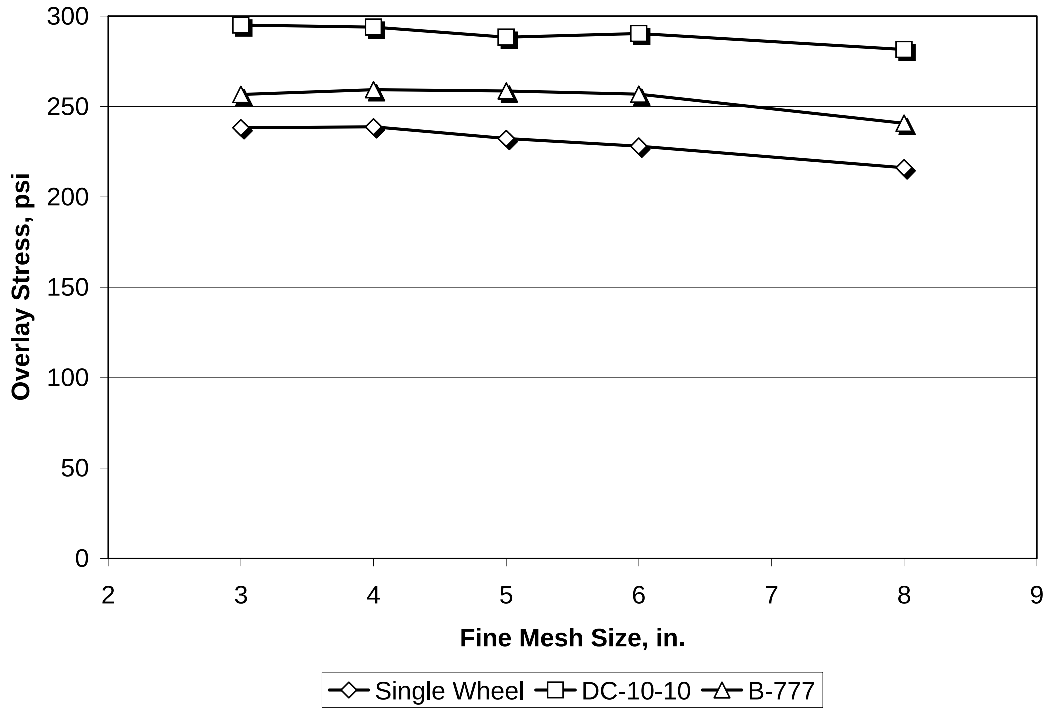

Figure 2. Horizontal stress computed at the bottom surface of the PCC overlay as a function of 3D-FEM mesh size in the fine mesh region.

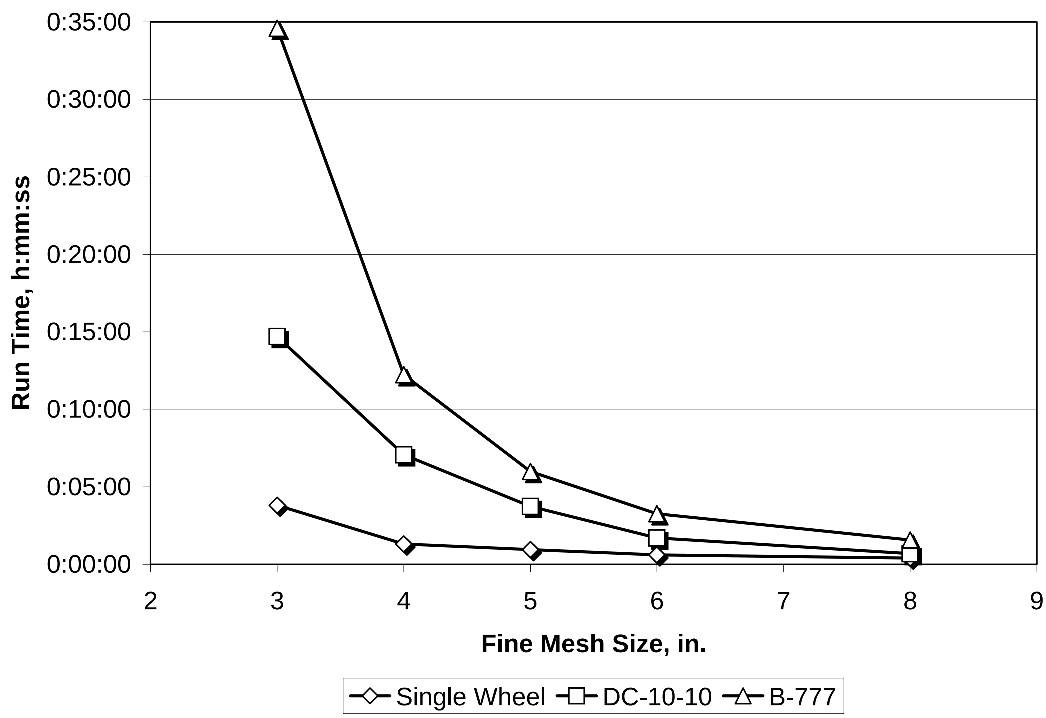

Figure 3. Run time as a function of 3D-FEM mesh size in the fine mesh region (life computation).

HANDLING AIRCRAFT MIXES WITH FEDFAA

FEDFAA can calculate the life or design thickness of a pavement structure for a traffic mix containing up to 20 aircraft. (In general, this may involve up to 40 separate load analyses, considering both 0° and 90° orientations of the gear relative to the slab edge. Furthermore, certain aircraft, e.g., the Airbus A380, require both wing gears and body gears to be analyzed.) When analyzing a pavement section, the aircraft in the mix are classified into four categories, according to table 1. All aircraft in the same category are analyzed with one call to the NIKE3D dynamic-link library (NIKE3D.dll), using an identical 3D-FEM mesh. With this arrangement, a maximum of four calls to NIKE3D.dll is sufficient to obtain all PCC slab and overlay edge stresses for the design or life calculation problem. Depending on the exact aircraft traffic mix, fewer calls are possible.

Table 1. 3D-FEM Mesh Characteristics for Aircraft Categories.

	Example	Fine Mesh Region Dimensions, in.	
Aircraft Category	Aircraft	*x*	*y*
I. Single Wheel, Dual Wheel	B-737	38	19
II. Dual Tandem (DT)	B-747	78	78
III. Triple Dual Tandem (TDT)	B-777	134	134
IV. Complex Gear Configurations	C-5, C-17A	285	285

The advantage of grouping aircraft into categories as above, rather than generating a separate 3D-FEM mesh for each aircraft, is that the numerical analysis is much more efficient for large aircraft mixes. In the 3D-FEM process, the greatest part of the computational effort is associated with the formation and factorization of the global stiffness matrix. In FEDFAA, this step is performed using a direct solution process to solve a set of linear equations. First, an initial solution is obtained assuming a nominal depth of interpenetration of the sliding contact surfaces. Then the solution is automatically iterated until the internal vertical forces generated at the sliding interfaces approximately balance the externally applied load. Both the direct solution step and the iteration procedure tend to be relatively time-consuming for contact problems. Therefore, a strategy that avoids duplicating these steps for every aircraft in the mix is desirable.

The approach adopted in the current version of FEDFAA is to treat each aircraft category (table 1) as a set of *n* simple load functions, where *n* is the number of aircraft in that category to be considered in the analysis (figure 4). Each load function takes on the value 1 at some time step, and 0 at all other time steps. (Here the term “time step” is used generically to refer to discrete changes in the load function; it does not refer to time in a real sense.) Hence, each “time step” is associated with exactly one aircraft load, and the number of “time steps” is equal to the number of loads needed for the analysis. In practice, this means that the full set of linear equations only needs to be solved for the first aircraft in the category. Responses for the subsequent aircraft loads are then obtained by back-substitution in the stored factorized matrix. Some iterations may be required for the subsequent aircraft, but the number of iterations is minimal since the starting point for the iteration procedure is the equilibrium point from the previous step.

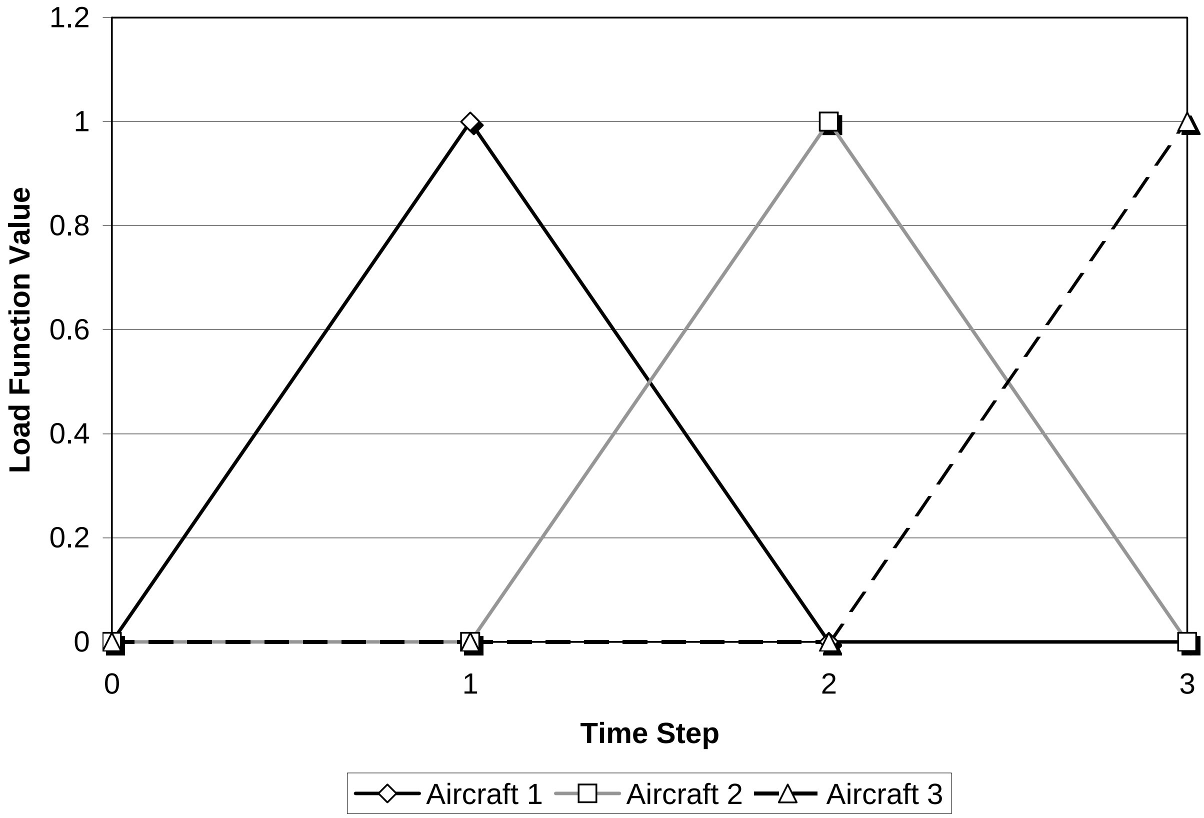

Figure 4. Load functions for analyzing a three-aircraft mix.

Source code modifications were made to both the calling procedure and to NIKE3D to implement the above procedure. One such modification involved the way in which aircraft data and computed stresses are passed back and forth between the 3D-FEM module and the FEDFAA calling procedure. In LEDFAA, maximum stresses are computed one at a time for a single aircraft and passed as single values back to the calling procedure. In FEDFAA, it was necessary to define new procedures for passing arrays containing data for multiple aircraft. Two data arrays were defined, containing the computed values of maximum edge stress for the PCC base slab and overlay, respectively. These values are computed in NIKE3D and returned to the calling program to be used in CDF and failure model calculations. The arrays are dimensioned to pass data for up to 40 aircraft.

COMPARISON OF PRELIMINARY FEDFAA OVERLAY DESIGNS WITH LEDFAA 1.3

FEDFAA directly computes slab edge stresses using 3D-FEM. This differs from the indirect procedure used in LEDFAA 1.3, whereby interior slab stresses are computed using LEA, and then converted to equivalent edge stresses using correlation equations. Since the response models are different, the rigid overlay designs using FEDFAA and LEDFAA 1.3 will also differ in general. For the purpose of planned FEDFAA model calibration for design of rigid overlays, preliminary calculations were made to compare LEDFAA 1.3 and FEDFAA overlay design thicknesses. Comparative designs were based on the traffic mix in Table 2, for the 24 pavement sections shown in table 3. For each pavement section, table 3 reports the LEDFAA 1.3 overlay thickness, the corresponding overlay thickness using FEDFAA beta, and the difference between them. It is noted that for stabilized structures and pavement structures with higher modulus subgrades, the difference is negative, i.e., FEDFAA designs thinner overlays than LEDFAA 1.3. The opposite is true for weaker pavement structures.

Table 2. Wide-Body Aircraft Traffic Mix.

Aircraft	Gross Weight, lbs.	Annual Departures
B737	110,000	3726
B727	209,500	2011
B707	257,000	1730
DC-9	135,000	855
DC-8	325,000	852
DC-10-10	443,000	827
B-747	600,000	280
B-767	315,000	237
B-757	255,000	127

PROGRAM MIGRATION TO VISUAL BASIC.NET

LEDFAA 1.3 is written in Microsoft™ Visual Basic™ 6.0 (VB6). A significant aspect of the FEDFAA software development is the changeover to Visual Basic.NET™ (VB.NET), the most recent update of Microsoft's Visual Basic programming language and the successor technology to VB6. Keeping up with the current technology has many advantages. VB.NET eliminates many known shortcomings of VB6, e.g., poor error-handling capabilities, no capabilities for multithreading, and "DLL Hell." Detailed explanations of these conditions are beyond the scope of this paper, but can be found in the applicable Microsoft technical literature [5].

VB.NET uses Common Language Runtime (CLR), which performs Automatic Memory Management (sometimes known as "Garbage Collection"). The result is better overall memory management than in VB6. Additionally, VB.NET applications are easier to test, debug, and support over the long term than VB6 applications.

The FEDFAA program requires installation of the .NET Framework, which is required by all VB.NET programs. The .NET framework installs quickly and can be downloaded free of charge from the Microsoft™ website.

Since VB.NET breaks compatibility with VB6, a considerable programming effort was required to upgrade the affected FEDFAA and LEAF components. Most of the source code was automatically upgraded using the VB.NET upgrade wizard. This utility produces an upgrade report with a list of project files, status of the upgrade, and the number of errors and warnings caused by the upgrade. Each error and warning are described and provided with a link to the right place in VB.NET help file for additional explanation. There were about 150 errors and 645 warnings for the FEDFAA upgrade and only about 121 warnings for the LEAF upgrade. Text-based program modules were easily upgraded. However, graphics modules (forms) did not automatically upgrade and had to be rewritten manually for the VB.NET environment.

Table 3. Comparisons of LEDFAA 1.3 and FEDFAA Beta Overlay Designs.

	Overlay Design Properties					Overlay Design Thickness, in.		
	Thickness, in./Modulus, ksi				SCI, base PCC			
No.	Existing PCC	Subbase 1	Subbase 2	Subgrade		LEDFAA 1.3	FEDFAA Beta	Diff.
1	14/2641	6/21.4	-	Inf./7.5	75	14.47	17.04	2.57
2	14/1598	6/21.4	-	Inf./7.5	50	16.38	18.23	1.85
3	14/2535	6/35.4	-	Inf./15.0	75	12.92	14.18	1.26
4	10/2641	6/21.4	-	Inf./7.5	75	17.11	17.97	0.86
5	10/1598	6/21.4	-	Inf./7.5	50	17.68	18.39	0.71
6	10/2641	6/35.4	-	Inf./15.0	75	15.96	16.61	0.65
7	14/2025	6/250	6/21.4	Inf./7.5	75	12.21	12.83	0.62
8	14/1598	6/35.4	-	Inf./15.0	50	15.14	15.68	0.54
9	10/1598	6/35.4	-	Inf./15.0	50	16.62	17.13	0.51
10	14/1598	6/250	6/21.4	Inf./7.5	50	14.71	15.14	0.43
11	10/2641	6/250	6/21.4	Inf./7.5	75	15.6	16.02	0.42
12	10/1598	6/250	6/21.4	Inf./7.5	50	16.28	16.66	0.38
13	10/2641	6/50.0	-	Inf./25.0	75	15.12	15.12	0
14	14/2430	6/50.0	-	Inf./25.0	75	11.65	11.59	-0.06
15	14/1598	6/50.0	-	Inf./25.0	50	14.26	14.18	-0.08
16	10/1598	6/50.0	-	Inf./25.0	50	15.87	15.73	-0.14
17	10/2641	6/500	6/35.4	Inf./15.0	75	14.48	14.07	-0.41
18	10/1598	6/500	6/35.4	Inf./15.0	50	15.28	14.5	-0.78
19	10/1598	6/700	6/50.0	Inf./25.0	50	14.93	13.51	-1.42
20	14/1598	6/500	6/35.4	Inf./15.0	50	13.49	11.8	-1.69
21	10/2641	6/700	6/50.0	Inf./25.0	75	14.07	12.28	-1.79
22	14/1598	6/700	6/50.0	Inf./25.0	50	13.09	10.34	-2.75
23	14/1832	6/500	6/35.4	Inf./15.0	75	10.71	7.19	-3.52
24	14/1832	6/700	6/50.0	Inf./25.0	75	9.82	3.00	-6.82

FEDFAA BETA TESTING

In-house alpha testing of FEDFAA was completed in August 2003. The primary goal of alpha testing was to verify that FEDFAA performs new rigid and rigid overlay life and design computations properly. A secondary objective was to verify that the upgrade to VB.NET was successfully completed and that most of the functionality is working properly. These two goals were completed, and the program has been made available for beta testing.

Currently, the program is posted on the web site of the FAA Airport Technology R&D Branch at http://www.airporttech.tc.faa.gov/naptf/download/index1.asp. It is available to the general public for beta testing. The FEDFAA program should be of interest to pavement engineers and designers, civil aviation authorities, aircraft industries, civil engineering faculty, and others with an interest in civil aviation infrastructure. Currently, the FAA is seeking feedback from users as part of the design procedure development process concerning FEDFAA and suggestions for how it could be improved. To that end, an online response form has also been posted to facilitate feedback from users.

FEDFAA 1.1 BETA is not a currently supported FAA design procedure. The thickness designs produced by FEDFAA 1.0 BETA for rigid pavements and overlays are thought to be reasonable, but they have not yet been calibrated against full-scale test data.

FUTURE WORK

The following activities are planned for future work:

- Continue to improve the 3D-FEM model to reduce the computational time and make it more suitable as a tool for airport pavement thickness design.

- Develop a revised fatigue model for rigid pavements based on existing full-scale test data and new full-scale test data from the National Airport Pavement Testing Facility (NAPTF). The failure model will be calibrated using stresses computed from the same 3D-FEM rigid pavement model to be used in the new design program.

CONCLUSIONS

This paper shows that 3D-FEM analysis can be successfully implemented in a new computer-based airport pavement design procedure. To date, the 3D-FEM stress analysis model has been integrated into the FAA airport pavement design program FEDFAA. The new program calculates the edge and/or interior stresses directly using the 3D-FEM tool. Preliminary results show that thickness designs are comparable with LEDFAA 1.3 and AC 150/5320-6D. Dividing aircraft into four categories and analyzing all aircraft in the same category with one call to NIKE3D achieved reduction in execution time for traffic mixes. The FEDFAA program is posted at the NAPTF web site http://www.airporttech.tc.faa.gov/naptf/download/index1.asp, and it is available to the general public for beta testing.

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